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14. ABSTRACT

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THE EARTH SYSTEM PREDICTION SUITE:

Toward a Coordinated U.S. Modeling Capability

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CAPSULE SUMMARY: Benefits from common modeling infrastructure and component interface standards are being realized in a suite of national weather and climate codes.

ABSTRACT

The Earth System Prediction Suite (ESPS) is a collection of flagship U.S. weather and climate models and model components that are being instrumented to conform to interoperability conventions, documented to follow metadata standards, and made available either under open source terms or to credentialed users.

The ESPS represents a culmination of efforts to create a common Earth system model architecture, and the advent of increasingly coordinated model development activities in the U.S. ESPS component interfaces are based on the Earth System Modeling Framework (ESMF), community-developed software for building and coupling models, and the National Unified Operational Prediction Capability (NUOPC) Layer, a set of ESMF-based component templates and interoperability conventions. This shared infrastructure simplifies the process of model coupling by guaranteeing that components conform to a set of technical and semantic behaviors. The ESPS encourages distributed, multi-agency development of modeling systems, controlled experimentation and testing, and exploration of novel model configurations, such as those motivated by research involving managed and interactive ensembles. ESPS codes include the Navy Global Environmental Model (NavGEM), HYbrid Coordinate Ocean Model (HYCOM),

and Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS®); the NOAA Environmental Modeling System (NEMS) and the Modular Ocean Model (MOM); the Community Earth System Model (CESM); and the NASA ModelE climate model and GEOS-5 atmospheric general circulation model.

BODY TEXT

The software infrastructure that underlies Earth system models includes workhorse utilities as well as libraries generated by research efforts in computer science, mathematics, and computational physics. The utilities cover tasks like time management and error handling, while research-driven libraries include areas such as high performance I/O, algorithms for grid remapping, and programming tools for optimizing software on emerging computer architectures. Collectively, this model infrastructure represents a significant investment. As a crude comparison, a comprehensive infrastructure package like the Earth System Modeling Framework (ESMF; Hill et al. 2004, Collins et al. 2005), is comparable in size to the Community Earth System Model (CESM; Hurrell et al. 2013), each at just under a million lines of code.[1]

In 2002, Dickinson et al. articulated the goal of *common* model infrastructure, a code base that multiple weather and climate modeling centers could share. This idea was shaped by an *ad-hoc*, multi-agency working group that had started meeting several years earlier, and was echoed in reports on the state of U.S. climate modeling (NRC 1998, NRC 2001, Rood et al. 2000). Leads from research and operational centers posited that common infrastructure had the potential to foster collaborative development and transfer of knowledge; lessen redundant code; advance

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[1] Codes compared are CESM 1.0.3, at about 820K lines of code (Alexander and Easterbrook 2011), and ESMF 6.3.0rp1, at about 920K lines of code (ESMF metrics available online at: https://www.earthsystemcog.org/projects/esmf/sloc_annual)

computational capabilities, model performance and predictive skill; and enable controlled experimentation in coupled systems and ensembles. This vision of shared infrastructure has been revisited in more recent publications and venues; for example, in the 2012 National Research Council report entitled *A National Strategy for Advancing Climate Modeling* (NRC 2012).

In this article we describe how the vision of common infrastructure is being realized, and how it is changing the approach to Earth system modeling in the U.S. Central to its implementation is an *Earth System Prediction Suite (ESPS),* a collection of weather and climate models and model components that are being instrumented to conform to interoperability conventions, documented to follow metadata standards, and made available either under open source terms or to credentialed users.

We begin by discussing how the U.S. modeling community has evolved toward a common architecture, and explain the role of the ESMF and related projects in translating that convergence into technical interoperability. We define what we mean by minimal interoperability and the behavioral rules needed to achieve it, and describe the ESPS code suite and its target inclusion criteria. We give examples of the adoption process for different kinds of codes, and of science enabled by common infrastructure. Finally, we examine the potential role of the ESPS in model ensembles, and consider areas for future work.

EMERGENCE OF A COMMON MODEL ARCHITECTURE

Several generations of model infrastructure development, described in the sidebar (**Linked and Leveraged** …) allowed for the evolution and evaluation of design strategies. A community of infrastructure developers emerged, whose members exchanged ideas through a series of international meetings focused on coupling techniques (e.g. Dunlap et al. 2014), comparative

analyses such as Valcke et al. (2012), and design reviews and working group discussions hosted by community projects such as CESM and ESMF.

Over time, model developers from major U.S. centers implemented similar model coupling approaches, based on a small set of frameworks: ESMF, the CESM Coupler 7 (CESM CPL7; Craig et al. 2012), which uses the lower-level Model Coupling Toolkit for many operations (MCT; Larson et al. 2005, Jacob et al. 2005), and the Flexible Modeling System (FMS; Balaji 2012). ESMF, CPL7, and FMS share several key architectural characteristics. First, they are all single executable frameworks, meaning that constituent components are called as subroutines by a top-level driver. Second, major physical domains such as atmosphere, ocean, land, sea ice, and wave models are wrapped with component interfaces, and the component interfaces are structured similarly, with arguments for fields imported, fields exported, and time information. Not all coupling technologies follow these patterns. For example, in the OASIS coupler (Valcke 2013) used by many European climate models, components are run as separate, linked programs or “multiple executables” and in general do not require that fields transferred between components pass through a component interface.

The design convergence of U.S. models created an opportunity for coordination that a new program was ready to exploit. The National Unified Operational Prediction Capability (NUOPC; see http://www.nws.noaa.gov/nuopc/), a consortium of operational weather prediction centers and their research partners, was established in 2007 with goals that included creating a global atmospheric ensemble weather prediction system and promoting collaborative model development. In support of these goals, NUOPC sought further standardization of model infrastructure, and formalized the concept of common model architecture (CMA; Sandgathe et al. 2009; McCarren et al. 2013). The CMA can be defined as a set of conventions that govern

the application programming interfaces (APIs) of model components, the “level of componentization,” and the protocols for component interaction. In general terms, models using the ESMF, CPL7, or FMS frameworks could be said to share the same CMA.

Despite the similarities in structure, the components under these different frameworks still required the implementation of a common translation layer to achieve a minimal level of interoperability. NUOPC defined this minimal level of interoperability as the ability of a component to execute without code changes within a driver that provides the fields that it requires, and to return with informative messages if its input requirements are not met. Unlike FMS and CESM, which are associated with specific modeling systems, the ESMF software is intended to support multiple modeling systems, and it emerged as the reference architecture and CMA implementation. With ESMF, the NUOPC consortium undertook formal codification of the CMA and its realization in widely usable (e.g. portable, reliable, efficient, documented) software.

ESMF AND THE NUOPC LAYER

ESMF is high performance software for building and coupling Earth system models. It includes a superstructure for representing model and coupler components and an infrastructure of commonly used utilities, including grid remapping, time management, model documentation, and data communications (see https://www.earthsystemcog.org/projects/esmf/). It was developed and is governed by a set of multi-agency partners that includes NASA, NOAA, the Department of Defense and the National Science Foundation. ESMF can be used in multiple ways: 1) to create interoperable component-based modeling systems; 2) as a source of libraries for commonly used utilities; 3) as a file-based offline generator of interpolation weights for many different kinds of grids; and 4) as a Python package for grid remapping.

The ESMF design, which evolved over a period of years through weekly community reviews and thousands of user support interactions, accommodates a wide range of data structures, grids, and component layout and sequencing options. The main constructs are gridded components (`ESMF_GridComp`) and coupler components (`ESMF_CplComp`). Physical fields are represented using `ESMF_Fields`, which are contained in import and export `ESMF_State` objects in order to be passed between components. ESMF defines three standard methods: initialize, run, and finalize, which can have multiple phases; however, there are no requirements on how these methods should behave. Since ESMF data structures can often reference native model data structures and ESMF methods can invoke model methods without introducing significant performance overhead, the software can serve either as a primary infrastructure or as a wrapper around components in existing coupled models.

ESMF provides interfaces and data structures with few constraints about how to use them. This flexibility enabled it to be adopted by many modeling systems,[2] but limited the interoperability across these systems. To address this issue, the NUOPC consortium developed a set of coupling conventions and generic representations of modeling system elements - drivers, models, connectors, and mediators - called the NUOPC Layer (see http://www.earthsystemcog.org/projects/nuopc/). NUOPC drivers and models can be understood in the usual way; connectors handle simple data transformations and transfers, and mediators implement field merges and custom coupling code. Table 1 summarizes NUOPC generic components and their roles. In some cases, the generic components may be used without modification; in others, user code is added at clear specialization points. Calls to NUOPC methods mainly relate to component creation and sequencing, and may be mixed with calls to

[2] ESMF components are listed here: https://www.earthsystemcog.org/projects/esmf/components

ESMF time management, grid remapping, and other methods.

The NUOPC Layer enables multi-component systems, including hierarchies and ensembles, to be assembled using pre-fabricated code. Figure 1 is a schematic of two simple model configurations built using generic components.

While use of the NUOPC Layer cannot guarantee scientific compatibility, it does guarantee a set of component behaviors related to technical interoperability. These are described in the *NUOPC Layer Reference* (2014). Specifically, it ensures that a component will provide:

(i) A GNU makefile fragment that defines a small set of prescribed variables, which a NUOPC application uses to compile and link with the component.

(ii) A single public entry point, called SetServices. Standardizing this name enables code that registers components to be written generically.

(iii) An *InitializePhaseMap*, which describes a sequence of standard initialize phases drawn from a set of *Initialize Phase Definitions*. For example, one standard phase advertises the fields a component can provide, based on standard names drawn from the Climate and Forecast conventions (CF; Eaton et al. 2011). Field names are checked and mapped to each other using a NUOPC *Field Dictionary*. Another standard phase instantiates the fields that will be used.

(iv) A *RunPhaseMap*, in which each phase must check the incoming clock of the driver and the timestamps of incoming fields against its own clock for compatibility. The component returns an error if incompatibilities are detected.

(v) Time stamps on its exported fields consistent with the internal clock of the component.

(vi) A finalize method that cleans up all allocations and file handles.

These constraints, involving build dependencies, initialization sequencing, and run sequencing, are the focus of the NUOPC Layer because they are required to satisfy the definition of minimal interoperability: that components will run without code changes if their required field inputs are satisfied, and will return with appropriate warnings if they are not. The constraints nonetheless allow for the representation of many different model control sequences. They also enable negotiation and contingencies to be represented in a structured way, a feature that becomes important in optimization of multi-component systems, where components may compete for resources.

The ESMF/NUOPC software distribution is suitable for broad use as it has an open source license, comprehensive user documentation, a suite of about 6500 regression tests that runs nightly on about 30 different platform/compiler combinations, and a user support team. Performance evaluation occurs on an ongoing basis, with reports posted at https://www.earthsystemcog.org/projects/esmf/performance. The software has about 6000 registered downloads.

THE EARTH SYSTEM PREDICTION SUITE

The National Earth System Prediction Capability (National ESPC; see http://espc.oar.noaa.gov) combines the ESPC, initiated in 2010, and NUOPC, to extend the scope of the NUOPC program in several ways. The National ESPC goal is a global Earth system analysis and prediction system that will provide seamless predictions from days to decades, developed with contributions from a broad community. Expanding on NUOPC, the National ESPC includes additional research agency partners (NSF, NASA, and DOE), time scales of prediction that extend beyond short term forecasts, and new modeling components (e.g. cryosphere, space).

In order to realize the National ESPC vision, major U.S. models must be able to share and exchange model components. Thus the National ESPC project is coordinating development of an *Earth System Prediction Suite (ESPS)*, a collection of NUOPC-compliant Earth system components and model codes that are technically interoperable, tested, documented, and available for integration and use. At this stage, ESPS focuses on *coupled modeling systems* and *atmosphere, ocean, ice* and *wave* components.

ESPS partners are targeting the following inclusion criteria:

- ESPS components and coupled modeling systems are NUOPC-compliant.
- ESPS codes are versioned.
- Model documentation is provided for each version of the ESPS component or modeling system.
- ESPS codes have clear terms of use (e.g. public domain statement, open source license, proprietary status), and have a way for credentialed ESPC collaborators to request access.
- Regression tests are provided for each component and modeling system.
- There is a commitment to continued NUOPC compliance and ESPS participation for new versions of the code.

ESPS is intended to formalize the steps in preparing codes for cross-agency application, and the inclusion criteria support this objective. NUOPC compliance guarantees a well-defined, minimal level of interoperability, and enables assembly of codes from multiple contributors. Versioning is essential for traceability. Structured model documentation facilitates model

analysis and intercomparison.[3] Clear terms of use and a way to request code access are fundamental to the exchange of codes across organizations. Regression tests are needed for verification of correct operation on multiple computer platforms. The commitment to continued participation establishes ESPS as an ongoing, evolving capability.

At the time of this writing, not all criteria are satisfied for all candidate codes. Further, the criteria themselves are likely to evolve. The extent of the metadata to be collected still needs to be determined, and specific requirements for regression tests have not yet been established. The process of refining the inclusion criteria and completing it for all codes is likely to occur over a period of years. However, a framework is now in place for moving forward. Current information is presented on the ESPS webpage, see https://www.earthsystemcog.org/projects/esps/.

Code Development, Compliance Checking, and Training Tools

The viability of ESPS depends on there being a straightforward path to writing compliant components. Several tools are available to facilitate development and compliance verification of ESPS components and coupled models. These include the command line-based NUOPC Compliance Checker and Component Explorer, both described in the *NUOPC Layer Reference* (2014), and the graphical Cupid Integrated Development Environment (IDE) (Dunlap 2014).

The NUOPC Compliance Checker is an analysis tool that intercepts component actions during the execution of a modeling application and assesses whether they conform to standard NUOPC Layer behaviors. It is linked by default to every application that uses ESMF and can be activated by setting an environment variable. When deactivated, it imposes no performance penalty. The

[3] Initial, minimal metadata associated with each ESPS model is being collected and displayed using tools from the Earth System Documentation consortium (ES-DOC; Lawrence et al. 2012).

Compliance Checker produces a compliance report that includes, for each component in an application, information such as checks for presence of the required initialize, run, and finalize phases, correct timekeeping, how fields are passed between components, and the presence of required component and field metadata.

The Component Explorer is a run-time tool that analyzes a *single* model component by acting as its driver. The tool offers a way of evaluating the behavior of the component outside of a coupled modeling application. It steps systematically through the phases defined by the component and performs checks such as whether required makefile fragments are provided, whether a NUOPC driver can link to the component, and whether error messages are generated if the required inputs are not supplied. For additional information, the Compliance Checker can be turned on while the Component Explorer is running. A test of NUOPC compliance is running the candidate component in the Component Explorer and ensuring that it generates no warnings from the Compliance Checker when it is turned on.

Cupid provides a comprehensive code editing, compilation, and execution environment with specialized capabilities for working with NUOPC-based codes. It is implemented as a plugin for Eclipse, a widely used IDE. A key feature of Cupid is the ability to create an outline that shows the NUOPC-wrapped components in the application, their initialize, run, and finalize phases, and their compliance status. The outline is presented to the developer side-by-side with a code editor, and a command line interface for compiling and running jobs. Cupid provides contextual guidance and can automatically generate portions of the code needed for compliance. The user can select several prototype codes for training, or can import their own model code into the environment. Figure 2 shows the Cupid graphical user interface.

Table 3 summarizes the tools described in this section and their main uses. Static analysis mode refers to the examination of code, while dynamic analysis mode refers to evaluation of component behaviors during run-time.

ADAPTING MODELS FOR ESPS

In this section, we describe the approach to adapting different sorts of codes for ESPS. We look at implementation of single model components, wholly new coupled systems, and existing coupled systems.

The realities of implementation required adjustments to some goals and strategies. Most significantly, the idea that a *single* common software framework must replace all others, a solution advanced in the 2012 NRC report, proved unrealistic and unnecessary. In practice, it has been more effective to wrap and combine multiple infrastructure packages, and ESMF often co-exists with native infrastructure within modeling applications. This approach also enables centers to maintain local differences in coupling methodologies; longstanding coupled modeling efforts at NCAR, GFDL, and NASA have established organizational preferences for handling coastlines, conservative transfer of fluxes, and other coupling operations. The details of these operations are not reviewed here; detailed discussion of techniques is available in documents such as Craig (2014). The different approaches encountered to date can be accommodated by the NUOPC Layer rules and software.

Single model components are the most straightforward to wrap with NUOPC Layer interfaces. The Modular Ocean Model (MOM5; Griffies 2012) and Hybrid Coordinate Ocean Model (HYCOM; Halliwell et al., 1998, Halliwell et al., 2000, Bleck, 2002) are examples of this case. Both ocean models had previously been wrapped with ESMF interfaces, and had the distinct

initialize, run, and finalize standard methods required by the framework. For NUOPC compliance, a standard sequence of initialize phases was added, and conformance with the Field Dictionary checked. The process of wrapping MOM5 and HYCOM with NUOPC Layer code required minimal changes to the existing model infrastructure. For both MOM5 and HYCOM, NUOPC changes can be switched off, and MOM5 can still run with GFDL's in-house FMS framework.

The construction of newly coupled systems is a next step in complexity. The Navy global modeling system and the NOAA Environmental Modeling System (NEMS; Iredell et al. 2014) are examples in this category. Navy developers coupled the Navy Operational Global Atmospheric Prediction System (NOGAPs; Rosmond 1992, Bayler and Lewit 1992) and HYCOM by introducing simple NUOPC connectors between the models, and were able to easily switch in the newer Navy Global Environmental Model atmosphere (NavGEM; Hogan et al. 2014) when it became available. This work leveraged ESMF component interfaces introduced into NOGAPS as part of the Battlespace Environments Institute (BEI; Campbell et al. 2010). The NUOPC-based HYCOM code from this coupled system was a useful starting point for coupling HYCOM with components in NEMS and the CESM.

NEMS is an ambitious effort to organize a growing set of operational models at the National Centers for Environmental Prediction under a unifying framework. Model coupling within NEMS began with coupling the Global Spectral Model or GSM (previously the Global Forecast System or GFS; EMC 2003) to HYCOM and MOM5 ocean components and the CICE sea ice model (Hunke and Lipscomb 2008). A NUOPC mediator and connectors were introduced in order to transfer and transform data on a potentially different grid and distribution than the component models, and to perform merging and other coupling operations. A prototype of the

atmosphere-ocean-ice system has been completed, but much work remains to validate the code, introduce additional components, and ready the system for operational use. Other components now being introduced into NEMS include the WaveWatch 3 model (Tolman 2002), the Ionosphere-Plasmasphere Electrodynamics (IPE) model (based on an earlier model described in Fuller-Rowell et al. 1996 and Millward et al. 1996), and a hydraulic component implemented using the WRF-Hydro model (Gochis et al. 2013). The Non-Hydrostatic Mesoscale Model (NMMB; Janjic et al. 2012) will be coupled within NEMS to the Princeton Ocean Model (POM; Blumberg and Mellor 1987) regional ocean for hurricane forecasts, and there are also plans to introduce an alternate ice model, KISS (Grumbine 2013). Shown schematically in Figure 3, all are being constructed as NUOPC components.

Adapting an existing coupled modeling system for NUOPC compliance is most challenging, since adoption must work around the native code. The CESM, the Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS; Hodur 1997, Chen et al. 2003), and ModelE (Schmidt et al. 2006) are examples of this. In CESM, a fully coupled model that includes atmosphere, ocean, sea ice, land ice, land, river and wave components, ESMF interfaces have been supported at the component level since 2010, when it was known as the Community Climate System Model 4.0. However, the CESM driver was based on the MCT data type. Recently, the driver was rewritten to accommodate the NUOPC Layer. By introducing a new component data type in the driver, either NUOPC component interfaces or the original component interfaces that use MCT data types can be invoked. These changes did not require significant modifications to the internals of the model components themselves.

Incorporating the NUOPC Layer into COAMPS involved refactoring the existing ESMF layer in each of its constituent model components and implementing a new top-level driver/coupler layer.

As with the global Navy system, ESMF component interfaces had been introduced as part of BEI. The COAMPS system includes the non-hydrostatic COAMPS atmosphere model coupled to the Navy Coastal Ocean Model (NCOM; Martin et al. 2009) and the Simulating WAves Nearshore model (SWAN; Booij et al. 1999). Refactoring to introduce the NUOPC Layer into each model component involved changing the model ESMF initialize method into multiple standard phases. The representation of import/export fields was also changed to use the NUOPC Field Dictionary. These changes were straightforward and limited to the model ESMF wrapper layer. An effort that is just beginning involves wrapping the NEPTUNE [Navy Environmental Prediction system Utilizing the NUMA (Nonhydrostatic Unified Atmospheric Model) CorE] atmosphere, a non-hydrostatic model which uses an adaptive grid scheme (Kelly and Giraldo 2012, Kopera et al. 2014, Giraldo et al. 2013), with a NUOPC Layer interface, as a candidate for the Navy's next-generation regional and global prediction systems..

When NUOPC Layer implementation began in ModelE, the degree of coarse-grained modularization was sufficiently complete that the ModelE atmosphere could be run with four different ocean models (data, mixed-layer, and two dynamic versions), and the two dynamic oceans could both be run with a data atmosphere. At this time, atmosphere and mixed layer ocean models are wrapped as NUOPC components, and can be driven using a NUOPC driver. Specification of the multi-phase coupled run sequence was easily handled via NUOPC constructs. Mediators will provide crucial flexibility to apply nontrivial field transformations as more complex coupled configurations are migrated.

Developers of the GEOS-5 atmospheric model (Molod et al. 2012) incorporated ESMF into the model design from the start, using the framework to wrap both major components and many sub-processes. In order to fill in gaps in ESMF functionality, the GEOS-5 development team

developed software called the Modeling Analysis and Prediction Layer, or MAPL. A challenge for bringing GEOS-5 into ESPS is translating the MAPL rules for components into NUOPC components, and vice versa. A joint analysis by leads from the MAPL and NUOPC groups revealed that the systems are fundamentally similar in structure and capabilities (da Silva et al. 2013). The feature that most contributes to this compatibility is that neither NUOPC nor MAPL introduces new component data types - both are based on components that are native ESMF data types (`ESMF_GridComp` and `ESMF_CplComp`). MAPL has been integrated into the ESMF/NUOPC software distribution, and set up so that refactoring can reduce redundant code in the two packages. Although the GEOS-5 model is advanced with respect to its adoption of ESMF, most of the work in translating between MAPL and NUOPC still lies ahead.

RESEARCH AND PREDICTION WITH COMMUNITY INFRASTRUCTURE

Community-developed ESMF and NUOPC Layer infrastructure supports scientific research and operational forecasting. This section describes examples of scientific advances that ESPS and related infrastructure have facilitated at individual modeling centers, and the opportunities they bring to the management of multi-model ensembles.

Modeling and Data Center Impacts

The use of ESMF and NUOPC infrastructure at modeling and data centers follows several patterns. The NUOPC Layer allows software components representing major physical realms to be leveraged across agencies; the underlying ESMF architecture wraps and organizes a diversity of components, both large and small; and ESMF grid remapping and other libraries are used extensively with coupled modeling systems and in other contexts such as data visualization.

- ***Navy NavGEM-HYCOM-CICE:*** The NavGEM-HYCOM-CICE modeling system, coupled

using NUOPC Layer infrastructure, is being used for research at the Naval Research Laboratory. An initial study, using just NavGEM and HYCOM, examined the onset of a Madden Julien Oscillation (MJO) event in 2011 (Peng, 2011). For standalone NavGEM, the onset signature was basically absent. The coupled system was able to reasonably simulate the onset signature compared with TRMM (Tropical Rainfall Measuring Mission) measurements. With the addition of the CICE ice model, this system is now being used to explore the growing and melting of sea ice over the Antarctic and Arctic regions.

- ***COAMPS and COAMPS-TC:*** The COAMPS model is run in research and operations by the Defense Department and others for short-term numerical weather prediction. COAMPS-TC is a configuration of COAMPS specifically designed to improve tropical cyclone (TC) forecasts (Doyle et al. 2014). Both use ESMF and NUOPC software for component coupling. The coupled aspects of COAMPS and COAMPS-TC were recently evaluated using a comprehensive observational data set for Hurricane Ivan (Smith et al. 2013). This activity allowed for the evaluation of model performance based on recent improvements to the atmospheric, oceanic, and wave physics, while gaining a general but improved understanding of the primary effects of ocean–wave model coupling in high-wind conditions. The new wind input and dissipation source terms (Babanin et al. 2010; Rogers et al. 2012) and wave drag coefficient formulation (Hwang, 2011), based on field observations, significantly improved SWAN's wave forecasts for the simulations of Hurricane Ivan conducted in this study. In addition, the passing of ocean current information from NCOM to SWAN further improved the TC wave field.
- ***GEOS-5:*** The NASA GEOS-5 atmosphere-ocean general circulation model is designed to

simulate climate variability on a wide range of time scales, from synoptic time scales to multi-century climate change. Projects underway with the GEOS-5 AOGCM include weakly coupled ocean-atmosphere data assimilation, seasonal climate predictions and decadal climate prediction tests within the framework of Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al. 2012). The decadal climate prediction experiments are being initialized using the weakly coupled atmosphere-ocean data assimilation based on MERRA (Rienecker et al. 2011). All components are coupled together using ESMF interfaces.

- ***NEMS:*** The NEMS modeling system under construction at NOAA is intended to streamline development and create new knowledge and technology transfer paths that bridge the NOAA research and operational centers and other agency efforts. NEMS will encompass multiple coupled models, including future implementations of the Climate Forecast System (CFS; Saha 2014), the Next Generation Global Prediction System (NGGPS; Lapenta 2015), and regional hurricane forecast models. The new CFS will couple global atmosphere, ocean, sea ice and wave components through the NUOPC Layer for advanced probabilistic seasonal and monthly forecasts. NGGPS is being designed to improve and extend weather forecasts to 30 days, and will include ocean and other components coupled to an atmosphere. The NEMS hurricane forecasting capability will have nested mesoscale atmosphere and ocean components coupled through the NUOPC Layer for advanced probabilistic tropical storm track and intensity prediction. Early model outputs from the atmosphere (GSM), ocean (MOM5), and sea ice (CICE) three-way coupled system in NEMS are currently being evaluated.
- ***CESM:*** The CESM coupled global climate model enables state-of-the art simulations of

Earth's past, present and future climate states and is one of the primary climate models used for national and international assessments. A recent effort involves coupling HYCOM to CESM components using NUOPC Layer interfaces. A scientific goal of the HYCOM-CESM coupling is to assess the impact of hybrid versus depth coordinates in the representation of our present-day climate and climate variability. The project leverages an effort to couple HYCOM to an earlier version of CESM, CCSM3 (Lu et al. 2013; Michael et al. 2013).

- ***Grid Remapping:*** An ongoing collaboration between CESM and ESMF led to joint development of the parallel ESMF grid remapping tools. These are now widely used by modeling groups and visualization and analysis packages including NCL and UV-CDAT, and have enabled projects like CESM to meet critical milestones and opened doors to new research initiatives. For example, leveraging ESMF grid remapping, CESM was able to create offline utilities that permit researchers to run CESM on user-defined grids, including regionally refined grids.[4] ESMF offline remapping has also enabled the incorporation of the Model for Prediction Across Scales (MPAS) ocean model as a new CESM component. Recent efforts are focusing on migrating the off-line grid remapping into a run time capability in order that more dynamic and adaptive grids can be supported.

ESPS Opportunities for Managed and Interactive Ensembles

In the weather and climate prediction communities ensemble simulations are used to separate signal from noise, reduce some of the model-induced errors and improve forecast skill. Uncertainty and errors come from several sources:

[4] These utilities have been folded into the publically released version of the model as of CESM1.2.0.

(i) Initial condition uncertainty associated with errors in our observing systems or in how the observational estimates are used to initialize prediction systems (model uncertainty/errors play a significant role here);

(ii) Uncertainty or errors in the observed and modeled external forcing. This can be either natural (changes in solar radiation reaching the top of the atmosphere, changes in atmospheric composition due to natural forcing such as volcanic explosions, changes in the shape and topography of continents or ocean basins), or anthropogenic (changes is the atmospheric composition and land surface properties due to human influences);

(iii) Uncertainties or errors in the formulation of the models used to make the predictions and to assimilate the observations. These uncertainties and errors are associated with a discrete representation of the climate system and the parameterization of sub-grid physical processes. The modeling infrastructure development described here is ideally suited to quantify uncertainty due to errors in model formulation, and where possible reduce this uncertainty.

To account for initial condition uncertainty it is standard practice to perform a large ensemble of simulations with a single model by perturbing the initial conditions. The ensemble mean or average is typically thought of as an estimate of the signal and the ensemble spread or even the entire distribution is used to quantify the uncertainty (or noise) due to errors in the initial conditions. In terms of uncertainty in external forcing, the model simulations that are used to inform the Intergovernmental Panel on Climate Change (IPCC) use a number of different scenarios for projected greenhouse gas forcing to bracket possible future changes in the climate. In both of the examples above, it is also standard practice to use multiple models to quantify

uncertainty in model formulation and to reduce model-induced errors.

The use of multi-model ensembles falls into two general categories both of which are easily accommodated by ESPS. The first category is an *a posteriori* approach where ensemble predictions from different models are combined, after the simulation or prediction has been run, into a multi-model average or probability distribution that takes advantage of complementary skill and errors. This approach is the basis of several international collaborative prediction research efforts (e.g., National Multi-Model Ensemble, ENSEMBLES), climate change projection (CMIP) efforts, and there are numerous examples of how this multi-model approach yields superior results compared to any single model (e.g., Kirtman et al. 2013). In this case, the multi-model average estimates the signal that is robust across different model formulations and initial condition perturbations. The distribution of model states is used to quantify uncertainty due to model formulation and initial condition errors. While this approach has proven to be quite effective, it is generally *ad hoc* in the sense that the chosen models are simply those that are readily available. The ESPS development described here allows for a more systematic approach in that individual component models (e.g., exchanging atmospheric components CAM5 for GEOS-5) can easily be interchanged within the context of the same coupling infrastructure thus making it possible to isolate how the individual component models contribute to uncertainty and complementary skill and errors. For simplicity we refer to the interchanging or exchanging component models as managed ensembles.

The second category can be viewed as an *a priori* technique in the sense that the model uncertainty is “modeled” as the model evolves. This approach recognizes that the dynamic and thermodynamic equations have irreducible uncertainty and that this uncertainty should be included as the model evolves. This argument is the scientific underpinning for the multi-model

interactive ensemble approach. The basic idea is to take advantage of the fact that the multi-model approach can reduce some of the model-induced error, but with the difference being that this is incorporated as the coupled system evolves. In ESPS we can use the atmospheric component model from say CAM5 and GEOS-5 *simultaneously* as the coupled system evolves, and for example, combine the fluxes (mean or weighted average) from the two atmospheric models to communicate with the single ocean component model. Moreover, it is even possible to sample the atmospheric fluxes in order to introduce state dependent and non-local stochasticity into the coupled system to model the uncertainty due to model formulation. Forerunners of the approach have been implemented within the context of CCSM to study how atmospheric weather noise impacts climate variability (Kirtman et al. 2009, Kirtman et al. 2011) and seasonal forecasts in the NOAA operational prediction system (Stan and Kirtman 2008).

FUTURE DIRECTIONS

Next steps include continued development of NUOPC-based modeling systems, ongoing improvements to ESPS metadata and user access information, exploration of the opportunities ESPS affords in creating new ensemble systems, and addition of capabilities to the infrastructure software itself. Whether to extend the ESPS to other types of components is an open question. Developers have already implemented NUOPC Layer interfaces on components that do not fall into the initial ESPS model categories, including the WRF-Hydro hydrology model, the Community Land Model (CLM), and the Ionosphere-Plasmasphere Electrodynamics (IPE) model.

The continued incorporation of additional processes into models, the desire for more seamless prediction across temporal scales, and the demand for more information about the local impacts of climate change are some of the motivations for linking frameworks from multiple disciplines.

The NSF-funded Earth System Bridge project is building converters that will enable NUOPC codes to be run within the Community Surface Dynamics Modeling System (CSDMS), which contains many smaller models representing local surface processes, and CSDMS codes to be run within ESMF. The ESMF infrastructure is also being used to develop web service coupling approaches in order to link weather and climate models to frameworks that deliver local and regional information products (Goodall et al. 2013).

A critical aspect of future work is the evaluation and evolution of NUOPC and ESMF software for emerging computing architectures. A primary goal is for common infrastructure such as the NUOPC Layer to do no harm, and allow for optimizations within component models. However, NUOPC infrastructure also offers new optimization opportunities for coupled systems. The formalization of initialize and run phases, which allows components to negotiate with each other for resources, holds great potential in dealing with systems that have an increasing number of components, and will need to run efficiently on accelerator-based compute hardware. Among the planned extensions to NUOPC protocols are hardware resource management between components and the negotiation of data placement of distributed objects. Both extensions leverage the ESMF "virtual machine" or hardware interface layer, already extended under the ESPC initiative to be co-processor aware. The awareness of data location can also be used to minimize data movement and reference data where possible during coupling. Finally, there is interest in optimizing the grid remapping operation between component grids in the mediator by choosing an optimal decomposition of the transferred model grid. This optimization requires extra negotiation between the components which could be made part of the existing NUOPC component interactions.

CONCLUSION

Through the actions of a succession of infrastructure projects in the Earth sciences over the last two decades, a common model architecture (CMA) has emerged in the U.S. modeling community. This has enabled high-level model components to be wrapped in community-developed ESMF and NUOPC interfaces with few changes to the model code inside, in a way that retains much of the native model infrastructure. The components in the resulting systems possess a well-defined measure of technical interoperability. The ESPS, a collection of multi-agency coupled weather and climate systems that complies with these standard interfaces, is a tangible outcome of this coordination. It is a direct response to the recommendations of a series of National Research Council and other reports recommending common modeling infrastructure, and a national asset resulting from commitment of the agencies involved in Earth system modeling to work together to address global challenges.

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SIDEBAR I:

LINKED AND LEVERAGED:
THE EVOLUTION OF COUPLED MODEL INFRASTRUCTURE

First generation (1996-2001) Model coupling technologies were initially targeted for specific modeling systems, often within a single organization. Infrastructure that arose out of model development during this period included the Flexible Modeling System (FMS) at the Geophysical Fluid Dynamics Laboratory, the Goddard Earth Modeling System (GEMS; NASA GSFC 1997), and the Climate System Model (CSM; Boville and Gent 1998) and Parallel Climate Model (PCM; Washington et al. 2000) flux couplers at NCAR. Each of these systems coordinated functions such as timekeeping and I/O across model components contributed by domain specialists, and implemented component interfaces for field transformations and exchanges.

Second generation (2002-2006) Recognizing similar functions and strategies across first generation model infrastructures, a multi-agency group formed a consortium to jointly develop an Earth System Modeling Framework (ESMF). ESMF was intended to limit redundant code and enable components to be exchanged between modeling centers. Also at this time, within DOE, the Common Component Architecture (CCA; Bernholdt et al. 2006) consortium introduced a more precise definition of components into the high performance computing community, and members of the Model Coupling Toolkit (MCT) project worked with CSM (now CCSM - the Community CSM) to abstract low-level coupling functions into the MCT general-purpose library and develop a new CCSM coupler (CPL7).

Third generation (2007-2014) A third generation of development began as multi-agency infrastructures began to mature and refactor code, assess their successes and deficiencies, and encounter new scientific and computational challenges. Both NASA, with the Modeling Analysis and Prediction Layer (MAPL; Suarez et al. 2007) and the National Unified Operational Prediction Capability (NUOPC), a group of NOAA, Navy and Air Force operational weather prediction centers and their research partners, added conventions to ESMF to increase component interoperability. Similar refactoring efforts took place in other communities such as surface dynamics (Peckham et al. 2013) and agriculture (David et al. 2010). The demands of high resolution modeling and the advent of unstructured grids pushed ESMF to develop new capabilities and products, and MCT and CCSM – now CESM - to introduce new communication options. In this wave of development, the capabilities of shared infrastructure began to equal or outperform those developed by individual organizations.

What next? (2015 -) Although some infrastructure projects have disappeared or merged, projects from all three generations of development are still in use, and increasingly their

interfaces may coexist in the same modeling system. Future development is likely to include more cross-disciplinary projects like the Earth System Bridge (see Peckham et al. 2014), which is defining a formal characterization of framework elements and behaviors (an Earth System Framework Description Language, or ES-FDL), and using it to explore how to link components that come from different communities that have their own infrastructures (e.g. climate, hydrology, ecosystem modeling).

SIDEBAR II

LIMITS OF COMPONENT INTEROPERABILITY

Possible image for Sidebar II.

NUOPC Layer compliance guarantees certain aspects of technical interoperability, but it does not guarantee that all components of the same type, for instance all NUOPC-wrapped atmosphere models, will be scientifically viable in a given coupled modeling system. A simple example of scientific incompatibility is one in which the exported fields available do not match the imported fields needed for a component to run. Other incompatibilities can originate in how the scope of the component is defined (i.e., which physical processes are included), and in assumptions about how the component will interact with other components. [5] For example, some modeling systems implement an implicit interaction between

[5] Alexander and Easterbrook 2011. provide a high-level look at variations in the component architecture of climate models.

atmosphere and land models while others take a simpler explicit approach. Whether or not a component can adapt to a range of configurations and architectures is determined as well by whether scientific contingencies are built into it by the developer. The components in the ESPS are limited to major physical domains since many of the models in this category, such as CAM, CICE, and HYCOM have been built with the scientific flexibility needed to operate in multiple modeling systems and coupling configurations.

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